CALCULATING SPACE STATION RESOURCE PRICES

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ABSTRACT

The International Space Station (ISS), when completed, will provide unparalleled facilities for long duration microgravity space research. Two often asked questions concern how much will the ISS cost to operate, and how much will a particular experiment/payload cost to operate while on-orbit. At JPL, we have addressed these two questions by developing several models that attempt to provide answers. Collectively these models allow for the calculation of Station resource shadow prices, which can be used to project full utilization costs for experiments/payloads and to guide Station evolution decisions by comparing marginal costs to "market prices". This paper describes how we calculate ISS resource shadow prices from the first-order cost minimization conditions using MESSOC and engineering cross-consumption models. We also discuss the implications for future crewed missions, such as a lunar or Mars base.

INTRODUCTION

The International Space Station (ISS) is one of the most ambitious and expensive projects ever undertaken. Over the past 15 years, the primary focus has been on development costs, rather than operations costs. Operations costs, however, are a large fraction—perhaps more than half—of the Station's life-cycle cost, even when discounted.

Over the past 15 years, NASA has sporadically supported the development of an operations cost model called MESSOC (Model for Estimating Space Station Operations Costs). MESSOC is a cost and resource estimating tool for the Station's mature operations phase. MESSOC provides the analyst with the ability to estimate the effects of changes in the design, configuration, operations, and policies of ISS on both operations costs and Station resources available for utilization. These resources include crew time, logistics availability, and payload upmass to orbit. As a consequence, MESSOC is a key model in calculating not only operations costs, but full ISS resource shadow prices.

The heart of MESSOC is a set of integrated equations and algorithms based on engineering and other causal relationships. These equations and algorithms are supported by extensive engineering databases containing logistics parameters (such as MTBF), training parameters, launch vehicle characteristics, facility data, and flight hardware and software parameters. The cost analyst using MESSOC enters a scenario from a modern graphical user interface (GUI). The scenario basically tells MESSOC what the Station looks like over time (the Configuration Profile) and what is happening on the Station over time (the Operations Profile).

From the scenario and engineering databases, the equations and algorithms calculate operations costs in 20 functional cost categories, such as spares and repairs, flight crew and flight controller training, mission planning, real-time operations implementation, and element processing. At the same time, MESSOC computes a panoply of (non-cost) operations variables, such as IVA and EVA maintenance hours by Station element.

The cost categories in MESSOC were selected to cover a generic set of operations functions and activities, and therefore are meaningful across international partners. In this way, identical functions or activities are costed using the same algorithms and equations. Table 1 shows MESSOC's 20 cost categories.

Table 1
MESSOC Cost Categories

- Space Station Control Center (SSCC)/Engineering Support Center (ESC) maintenance and support
- Training operations
- Flight design
- Flight planning
- Flight implementation
- Sustaining engineering
- Software Support Environment (SSE), and information systems support
- Other Integrated Logistic Support (ILS)
- Intermediate/depot-level repair
- Flight equipment spares
- Element processing/reprocessing
- Station consumables
- Ground Support Equipment (GSE) maintenance and support
- User integration operations
- Flight crew pay and allowances
- Integration management and institutional support
- Program taxes and reserves
- NSTS/ELV launch services
- Data handling operations
- Tracking and Data Relay Satellite System (TDRSS)/NASCOM services

To some, the absence of on-orbit functions from these categories may seem to be an oversight, but a moment's thought leads to the realization that no money changes hands on-orbit; all resources are bought and paid for "on the ground." On-orbit time utilization is extremely important for operations effectiveness, however, and this is emphasized by the extensive calculations made for on-orbit crew time.

MESSOC ARCHITECTURE

As mentioned earlier, MESSOC contains a set of integrated cost and operations performance algorithms. Inputs to these algorithms are supplied through MESSOC's graphical user interface and Excel-like data tables. The user interface allows the analyst to construct a Space Station scenario by editing parameters and making choices within a set of programmatic, logistics, transportation, and crew factor dialog boxes, along with two spreadsheets, called the configuration profile and the operations profile. The configuration profile allows the analyst to describe the Station in terms of on-orbit hardware elements over the period of time for which cost estimates are desired. The operations profile allows the analyst to represent the overall structure of on-orbit and ground operations over the same period. MESSOC uses the Marshall Engineering Thermospheric (MET) Model, run separately, to compute average atmospheric densities for calculating drag forces on the Station during operations. A macro-view of MESSOC's architecture is shown in Figure 1.

Supporting Data Tables

The configuration profile is supported by several logistics data tables that contain detailed information on each orbital replacement unit (ORU) contained in each flight hardware element. This information covers on-orbit and ground maintenance characteristics such as mean time between failure (MTBF), how each failed ORU is to be treated, who will maintain it, how long each maintenance task (both corrective and preventive) will take, what parts (SRUs) might be used to effect repair, as well as data on weight and price.

The configuration profile is also supported by a data table containing, for each on-orbit hardware element, its physical parameters, such as overall element mass and frontal area, as well as data on transportation, processing, and sustaining engineering parameters. A separate data table relates (facility-class) orbital research facilities (ORFs) to the on-orbit hardware elements in which they are located.

The operations profile is supported by several distinct data tables. Training data tables provide the link between the flight crew, ground personnel, and launch site personnel requirements and training operations costs. A facilities data table provides detailed information on each major ground facility and operations support center, and a launch vehicle data table provides detailed characteristics of those launch systems that might be used to support Station.

MESSOC's data tables are in 3rd normalized form following modern relational database management

practices. This structure has the advantage that data changes are far less error-prone since an attribute value appears once and once only. The data in MESSOC are not intended as replacements for existing engineering, logistics, and training databases, but as copies of them. Consequently, to produce cost estimates that reflect the most current Space Station program, these data tables must be maintained in a timely fashion.

MESSOC's Algorithms and Equations

MESSOC's algorithms and equations are based on the principle that costs can be causally related to program decisions on Station design, configuration, operations, and logistics policies. It was strongly felt that greater Station complexity, activity rates, and/or Station size should give rise to greater estimated operations costs **in a systematic way**. Further, to the extent that the many options could be anticipated, MESSOC was designed to handle a variety of policies. For example, when properly used, MESSOC ought to be able to recognize the implications of shifting an activity from the Station to a ground facility.

This capability is illustrated by the logistics equations that determine the cost of Station ORU repairs and spares. The key drivers in both repair and spares costs are the demand generated by failures of ORUs. These demands can be generated on the Station, or by ground activities such as element processing. The greater the number of failures, the higher repair and spares costs are. For on-orbit failures, maintenance crewhours and spares upweight requirements are higher as well, though some demands generated by failures on the Station may be satisfied by on-orbit repair.

MESSOC's logistics algorithm calculates the demand rate for each ORU from the following sources:

- True failures of ORUs on the Station;
- False removals of ORUs on the Station — that is, ORUs that seem to have failed, but later retest-OK (RTOK) during additional testing on the ground;
- "Excess" removals generated by preventive maintenance policies such as replacing an ORU at X percent of its estimated MTBF;
- True failures of ORUs on the ground during pre-launch processing;

- False removals on the ground during pre-launch processing;
- Failures revealed during testing on the ground of ORUs drawn from inventory.

The logical relationship in MESSOC among variables leading to the calculation of repair demand rate for each ORU can be described in the repair flow shown in Figure 2. While the complete set of equations is far too long to publish here, the basic equations are reproduced below. For a complete set of equations, the reader is referred to the MESSOC Version 3.0 User Guide that comes in HTML format with the full model.[1]

$$\text{TRUEFAILURES/DAY}_{q,i} =$$

$$\sum_{p \in P(q,i)} (24\, UR_p / MTBF_p)\, [QPA_p] \qquad (1)$$

$$\text{TRUERETURNS/DAY}_{q,i} =$$

$$\sum_{p \in P(q,i)} (24\, UR_p / MTBF_p)\, [QPA_p]\, (1 - RIO_p) \qquad (2)$$

$$\text{TRUERETURNS/LOGCYC}_{q,t} =$$

$$[\text{DAYS/LOGCYC}_t] \sum_i [\text{TRUERETURNS/DAY}_{q,i}]\, [NE_{i,t}] \qquad (3)$$

$$\text{TRUEREPAIRS/LOGCYC}_{q,t} =$$

$$(\, [\text{TRUERETURNS/LOGCYC}_{q,t}\,] +$$

$$[\text{TRUEGRDREM/LOGCYC}_{q,t}]\,)\, X$$

$$(\, (1 - [\,AFI_q\,]\,[\,RTOK_q\,]\,) / [\,AFI_q\,]\,(1 - [\,RTOK_q\,])\,)\, \qquad (4)$$

where:

UR_p = utilization rate for ORU application p;
$MTBF_p$ = mean time between failure for ORU application p (in hours);
QPA_p = quantity per ORU application p;
$P(q,i)$ = set of applications of unique ORU q in Station element i;
RIO_p = repair-in-orbit rate for ORU application p;
$RTOK_q$ = retest-OK rate for ORU q;
AFI_q = inventory acceptance rate for ORU q;
$NE_{i,t}$ = number of Station elements of type i at time t.

In the above equations, the reader should note how Eq.(4) simplifies when AFI is one, and/or when RTOK is zero.

Repair costs are calculated for each ORU using the above calculated repair demand rates. MESSOC then annualizes the costs and sums over all ORUs to obtain the an annual repair cost in a given year. ORUs that are uneconomic to repair are condemned. Some of these condemnations may take place at KSC or at the vendor/depot. In any case, the number of condemnations, driven by the repair demand rates, is an important driver of the spares costs in MESSOC.

Looking at Figure 2, one might think that by increasing the repair-in-orbit (RIO) rate, the cost of repairs should go down since fewer ORUs are pumped into the repair flow. Further, even though SRUs might be needed to effect repairs, the overall cost of buying and transporting spares to and from the Station should also go down. The problem is that repairing ORUs on-orbit consumes valuable (and costly) crewhours that could otherwise be used be for the Station's primary mission— conducting science and technology experiments. To resolve whether more repair-in-orbit is a sound economic trade, one needs to know how much crewhours cost, and how much transportation to and from the Station costs. In other words, what are the "shadow prices" of these resources.

MESSOC alone does not and cannot provide these shadow prices. MESSOC computes the costs associated with adding a crew person to the Station. Adding more crew, however, consumes more transportation (for food, ECLSS supplies, etc.) and more power (for ECLSS). Adding more transportation, in turn, consumes more crewhours (for logistics transfers), and adding more power consumes more maintenance, both crewhours and transportation for ORUs. To compute shadow prices for resources, MESSOC also needs a Station Description Matrix (SDM) that takes into account these self- and cross-consumptions.

STATION DESCRIPTION MATRIX (SDM)

In computing shadow prices correctly, one must hold constant the amount of resources available for utilization. For example, the desired amount of power available for users might be set at 35 kW. Balancing Station utilization resource consumption and gross production means:

$$X_i = \sum_j A_{ij}(X_j) + U_i \quad \text{for } i = 1, 2, \ldots, N \qquad (5)$$

where:

X_i = Gross production (supply) of resource i;
$A_{ij}(X_j)$ = Cross-consumption of resource i used to produce X_j;
U_i = Desired utilization amount of resource i.

Equation (5) says that for each resource i, total production, X_i, must equal the total amount consumed in the production of all the other resources plus the amount to be made available to users (utilization). The Station Description Matrix, **A**, represents all the self- and cross-consumptions as functions of the resource amounts produced. The SDM is then a set of N engineering equations with N unknowns, representing the flow of Station resource inputs and outputs. Building the SDM requires a detailed understanding of the workings of the Station's subsystems.

Shadow prices can be properly computed by solving the following constrained minimization problem:[2]

$$\min C(X_1, X_2, \ldots, X_n)$$

subject to $\quad U_i = X_i - \sum A_{ij}(X_j) \geq U_i^*$
and $\quad X_i \geq 0$
for all $\quad i = 1, 2, \ldots, N$

where U_i^* is the Station's utilization requirement for resource i, that is, the amount to be made available to users.

The shadow price for each resource is the corresponding Lagrangian multiplier in the above constrained minimization problem. Switching to vector notation, the set of shadow prices, **p**, is solved from the first–order conditions as:

$$\mathbf{p} = (\mathbf{I} - \mathbf{H}^{\mathrm{T}})^{-1}\mathbf{C}' \qquad (6)$$

where **H** is the n x n matrix of *marginal* cross-consumption rates with n Station resources and **C'** is the vector of direct marginal costs. That is,

$$H_{ij} = d\,A_{ij}(X_j) / d\,X_j \qquad (7)$$
and
$$C_i' = d\,C / d\,X_i \qquad (8)$$

The **H** matrix is likely to contain many zero elements, indicating no marginal cross-consumptions. For IVA and EVA resources consumed in Station maintenance, MESSOC is easily capable of providing the needed quantitative values.[3]

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Computing the Shadow Prices

One of the advanced capabilities in MESSOC is the ability to compare two runs, essentially two scenarios, so as to isolate only those costs and operations variables that have changed. By taking advantage of the "Compare" function in MESSOC, the vector of direct marginal costs, C', can be computed at the same time as marginal cross-consumptions for those resources modeled in MESSOC.

Table 2 shows the primary on-orbit resources for which shadow prices are being developed initially (all metrics are per unit time).

Table 2
Primary On-Orbit Resources

- IVA (Crewhours)
- EVA, Station-Based (Crewhours)
- EVA, STS-Based (Crewhours)
- Pressurized Upmass (kgs)
- Unpressurized Upmass (kgs)
- Pressurized Downmass (kgs)
- Internal Rack Accommodations (Rack-hours)
- External Payload Accommodation (APAE-hours)
- Centrifuge Accommodations (Centrifuge-hours)
- Power (kW)
- SSRMS (Robot-hours1)
- SPDM (Robot-hours2)
- Communications (kb)

Other (TBD) secondary resources might be helpful to model the primary resources.

Short-Run Versus Long-Run Costs

In the short run, the Station cannot be expanded, but in the long run, additional Station modules can be added and systems evolved. In computing C' and the marginal cross-consumptions using MESSOC, one starts with the baseline Assembly Complete (AC) scenario. Sunk costs—those occurring prior to AC—play no role (other than reducing the cost of future design and development of Station elements). Only future operations costs and Station evolution costs are used.

The baseline AC scenario contains an AC configuration of the Station with its inherent resource capacities (e.g., power, volume, and crewhours). At that exact capacity, the long-run marginal cost and short-run marginal cost are equal in accordance with standard economic theory. However, the short-run marginal cost curve is steeper than the long-run marginal cost curve (at every output level). Hence, below the capacity inherent in the baseline AC configuration, the short-run marginal cost is below the long-run marginal cost. MESSOC can be used to compute both representations of direct marginal cost.

APPLICATIONS

Two often asked question concerning the ISS are how much will the Station cost to operate and how much will a particular payload cost to operate. MESSOC provides an answer to the first. The second requires that the correct resource shadow prices are known, the computation of which requires MESSOC and the SDM.

In conjunction with MESSOC and the SDM, we are developing a simple user interface to help a payload designer determine the (full) operations cost of a particular payload or experiment. The payload designer will call up a dialog box that asks for the amount of each resource type in Table 2 needed by the payload. For example, a payload designer should know the payload or experiment's physical volume requirements (i.e., standard rack equivalents), power requirements, IVA and EVA maintenance requirements and so on, as part of the normal payload integration planning process. The software will then respond with the operations cost.

Should the baseline MESSOC scenario or some of MESSOC's supporting data change, the software recomputes the shadow prices, and responds with the new operations cost for the payload. Using this capability, the payload designer can redesign the payload or experiment so as to create a more efficient use of the Station. This is especially useful in an ISS pricing regime based on charging the marginal cost of the Station resources provided. The payload designer then has strong incentives to optimize the design of the payload or experiment if resources must be paid for (with real dollars or "NASA" dollars), rather than being allocated by a central planner. No such optimization incentive exists when Station resources for a payload or experiment are fixed and allocated in advance.

The same argument holds for the Space Station Program Office in making Station evolution

decisions. Demand-based pricing is to be implemented for a portion of Station resources. A comparison of the resultant "market prices" against the computed shadow prices provides a basis for determining which resources need to be "grown." For example, if crewhours command a market price in excess of the marginal cost (i.e., shadow price) of adding crewhours, then an economic argument exists in favor of some expansion of the Station in that direction.

Beyond ISS, it is likely that NASA will undertake another large-scale human exploration initiative. Undecided as yet, it might be a lunar base or Mars base. Either way, there is an important role for models that estimate life-cycle cost and marginal costs (shadow prices) in a design-to-cost process. Life-cycle cost models are needed to address the issue of whether system requirements can be met within the budget constraints that may be imposed. Long-run marginal costs—that is, the gradient of the cost function—are needed to perform trade studies that move the design toward the most cost-effective one. Specially modified versions MESSOC and the SDM can serve as the basis for design-to-cost efforts in these future programs.

REFERENCES

[1] MESSOC Version 3.0 User Guide (forthcoming in HTML)

[2] Chamberlain, R. G., et al., "A Design Optimization Process for Space Station Freedom", JPL Pub 90-23, June 15, 1990

[3] Merrill, Orin, et al., "SDTM Station Description (Version 1.3)", JPL Systems Office, October 1, 1990
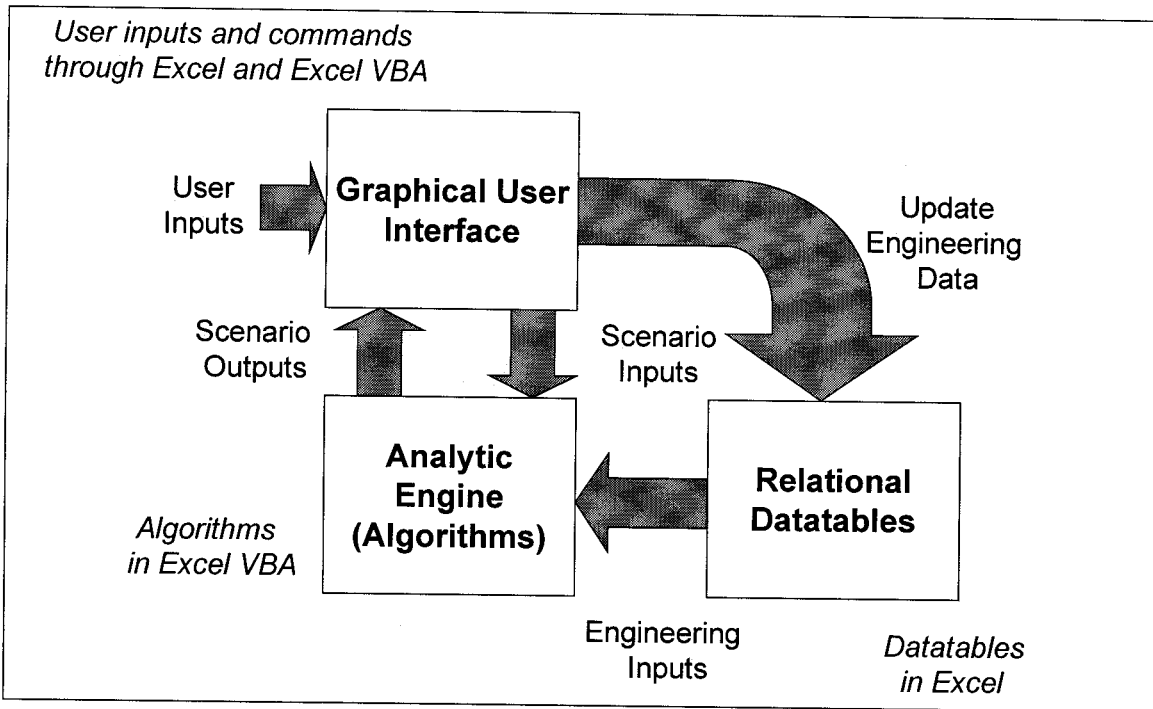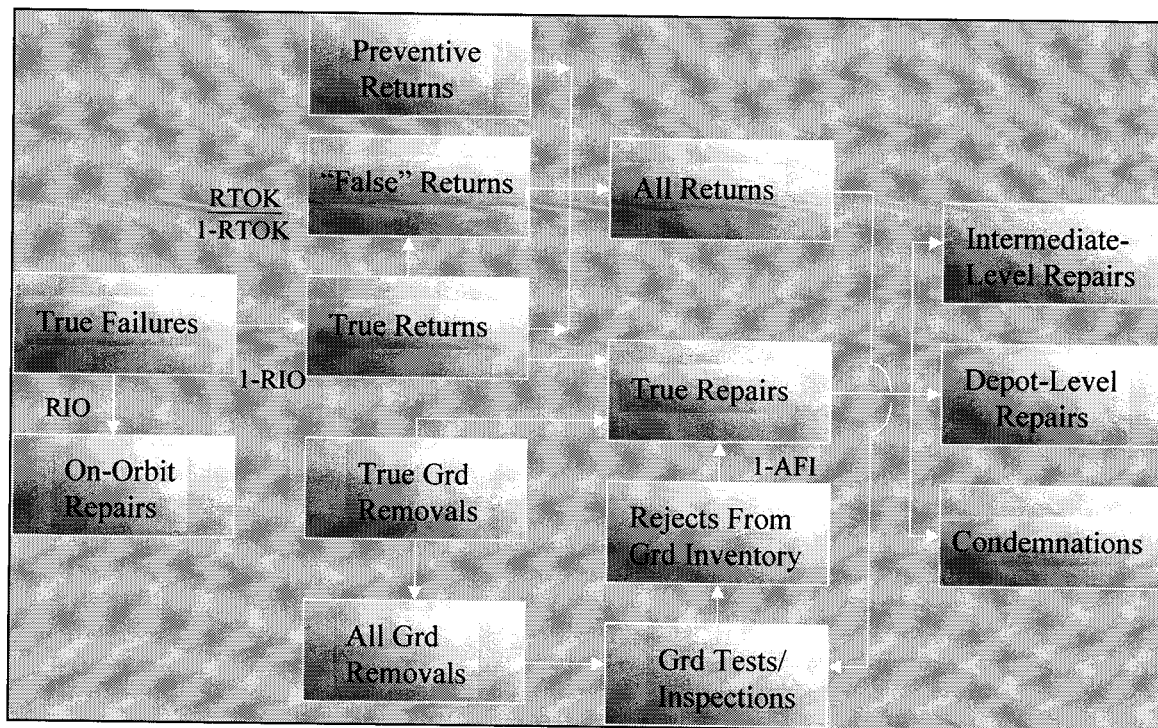
Figure 1 — MESSOC Version 3.0 Architecture

Figure 2 — MESSOC Repair Flow for Typical ORU

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